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Trends in Ecomaterials

— Approach of Materials Science to Global Environmental Problems —

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4.1 Introduction

The year of 2002 is the 10th anniversary of the Environmental Summit, formally the United Nations Conference on Environment and Development that was held in Rio de Janeiro in June 1992. This year is also the 30th anniversary of the United Nations Conference on the Human Environment, commonly called the Stockholm Conference, at which various environmental issues such as global environmental problems and sustainable development and growth are raised. After such initial calling of attention, environmental problems have been widely recognized, preceding attempts have been made, the framework has been discussed, and now we are at the stage where concrete measures for solutions will be taken. In this very year of 2002, the "World Summit for Sustainable Development" (Environmental Development Summit) was held in Johannesburg from August 26 to September 4. It was also resolved in a conference of the United Nations to request all the countries of the world to depart from mass consumption, mass production and mass disposal, and to change the industrial structures.

Under such circumstances, it goes without saying that we must recognize the responsibility and roles in terms of the global environment regarding the materials technology that has sustained the life and industry of human beings since old times, and that we must actively propose how the materials technology should be developed as a basic technology for the future society. "Ecomaterial" is a concept that was proposed by Japan for the first time in 1991 in advance of the Rio de Janeiro Summit.[1] Since the volume of material flow on the earth is enormous, the impact of ecomaterials on the environment is expected to be significant. Therefore, it is no exaggeration to say that success in obtaining ecomaterials largely affects the fate of global environmental issues. Taking such circumstances into consideration, we would like to review the technical trends in ecomaterials (approach of materials science to global environmental issues) and present an outlook for the future.

4.2 Ecomaterials cover a wide area

4.2.1 Definition of ecomaterial

"Ecomaterial" was a concept created in 1991 as a conclusion of the discussion in the Rare Metals Forum of The Society of Non-Traditional Technology on what the next-generation structure materials should be. The term was defined as "substances and materials that serve the sustainability of human society in harmony with the global environment." Figure 1 shows the performances of ecomaterials in terms of the three axes.[2] The axis of Innovation Frontier

Figure 1: Carbon nanotube transistor

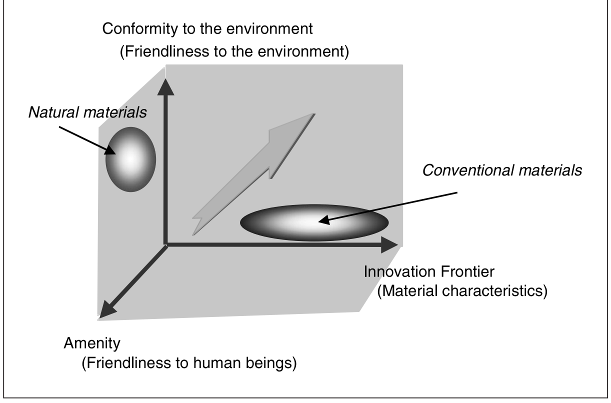
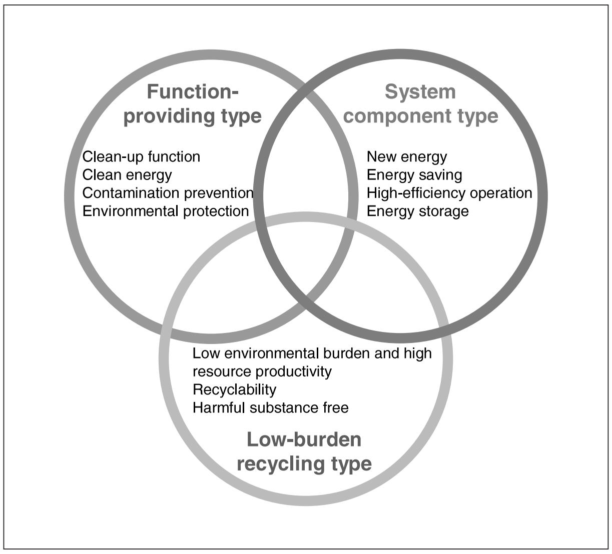


Figure 2: Classification of ecomaterials



indicates conventional material performances. Conformity to the environment represents how small the burden is to the environment, indicating the friendliness of materials to the environment from the viewpoint of sustainable development. Finally, the Amenity axis represents the index showing the friendliness to human beings (biocompatibility, non-allergic, and feeling of warmth are good examples). While conventional materials have pursued only performances, ecomaterials seek for the optimization in this new coordinate system. At present, those materials that have higher values of environmental efficiency represented by equation (1) in comparison with similar conventional materials are considered to be ecomaterials.[3]

Environmental efficiency (EE) = material performance (P) / environmental burden (BL)··················(1)

Therefore, in all the material groups including superconducting materials, semiconductors and magnetic materials, there are groups of ecomaterials and those with low environmental efficiency.

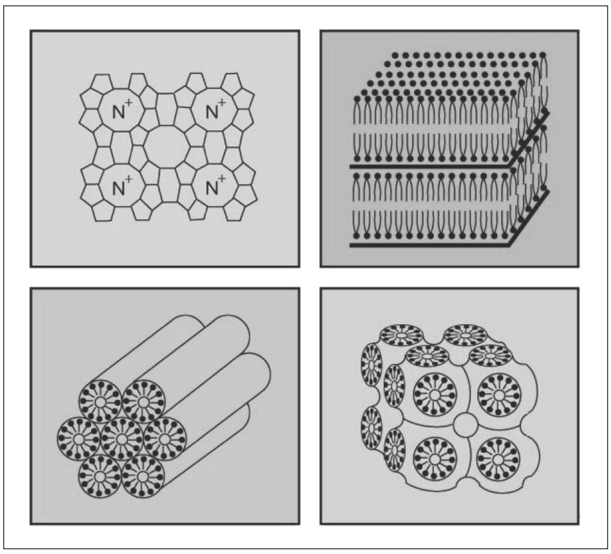
4.2.2 Classification of ecomaterials

From the viewpoint of behavior toward the global environment, ecomaterials are classified into three major groups as shown in Figure 2.[4] The first group is the function-providing type in which mainly the chemical functions of materials such as cleaning function and catalytic function are directly utilized. The second group is the system component type, which is required for the realization of highly efficient, clean energy systems. And the third group is the low-burden recycling type, in which materials themselves are not actively used in environmental systems but contribute to the conservation of the environment through their friendly characteristics such as recyclability. This classification is not overly strict, and the more practical the materials become, the more it is required for the materials to have combined characteristics. That is, materials corresponding to the overlapped portion in Figure 2 are required. Furthermore, although “free of harmful substance” is a characteristic of the low-burden recycling type, it goes without saying that all the materials must aim for this characteristic. The following is a brief introduction of typical materials and research topics for each group.

4.2.3 Functioning directly to the environment — Function-providing type —

A typical example of the function-providing type is catalyst. The success of the three way catalyst for the auto exhaust developed in the 1970s had a large impact by making it possible to simultaneously reduce hydrocarbons, carbon monoxide, and nitrogen oxides. One catalyst attracting particular attention at present is the photocatalyst. There are two directions of approach to the catalysts of this type, which are

Figure 3: Structure of zeolite



Source: Web site of Ecomaterials Center [10] activated by the energy of sunlight to decompose water. One direction is to make it possible to respond to visible rays so that water is efficiently decomposed producing hydrogen, and the other direction is to utilize the reaction in the range of ultraviolet rays so that cleaning functions are obtained.

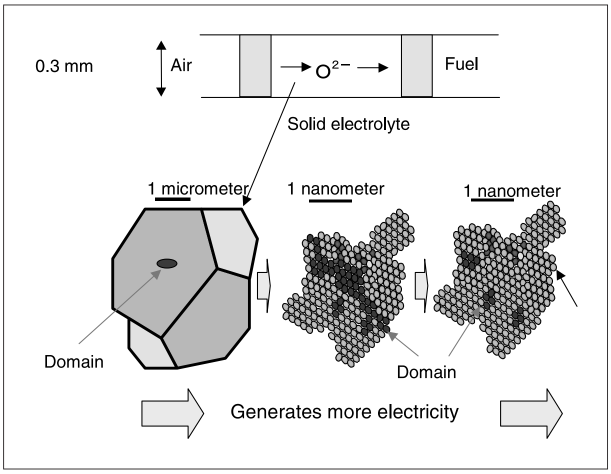
Regarding cleaning functions, the function that removes harmful substances such as environmental hormones and heavy metals is important. Many of the harmful substances now causing serious problems remain toxic even in diluted concentrations or are very difficult to decompose. To cope with such situation, technologies to decompose and separate harmful substances using large equipment in special fields (such as supercritical regions and strong magnetic fields) are being developed. On the other hand, research on systems of soft reactant substances that utilize the reaction at the solid-liquid interface such as absorption and desorption in materials having fine pores is being conducted simultaneously. Zeolite derived from natural resources is a typical example of such materials (Figure 3). Zeolite systems are expected to play an important role especially in the case where in situ clean-up function is required in the future living space.

The environmental materials of the function-providing type that make use of the chemical characteristics of materials further include a wide range of materials such as those for fixing carbon dioxide and catalysts to decompose dioxin and organic chlorine compounds. Regarding the above-mentioned three way catalyst, deterioration of catalyst activity has become a problem because the oxygen concentration in the exhaust increases in lean burning engines. Consequently, the development of catalysts that function under such lean burning conditions are demanded. In order to cope with these various environmental problems, innovation in materials technology is being sought for.

4.2.4 Core components of energy systems — System component type —

Heat resisting materials for high efficiency power generation are typical examples of the system component type. Since the efficiency of heat engines increases as the temperature

Figure 4: Solid electrolyte having nanostructure



difference of heat sources increases, in order to efficiently convert heat to electricity with less generation of carbon dioxide, it is necessary to obtain conditions that enable operations at high temperatures. Under such conditions, as it is required to rotate turbine blades at high temperatures and speeds, it becomes the key point for raising the temperature of the combustion gas of natural gas and other fuels to develop heat resisting materials for the turbine blades. Therefore, for the construction of environmentally friendly energy systems, materials technologies that support the systems construction are required, and those materials that provide such mechanical, thermal, chemical, or electrical characteristics are grouped as the ecomaterials of the system component type.

Also in the development of fuel cells that are attracting particular attention now, materials for separators and solid electrolytes are considered to be the key to constructing fuel cells systems. For example, solid electrolytes consist of micro fine regions called “domains,” and the penetrating power of ions increases significantly improving the electrical performances as these domains are uniformly distributed (see Figure 4). Such control of nanostructures is essential for improving the materials of the system component type, so that losses in the processes of energy generation and conversion are eliminated.

Hydrogen, which is also used for fuel cells, is considered to be the key material for the 21st century as the secondary energy, and it requires various materials for purification, transportation, storage and energy conversion. For example,

Figure 5: Diagram showing the principle of the metallic hydrogen saparation membrane

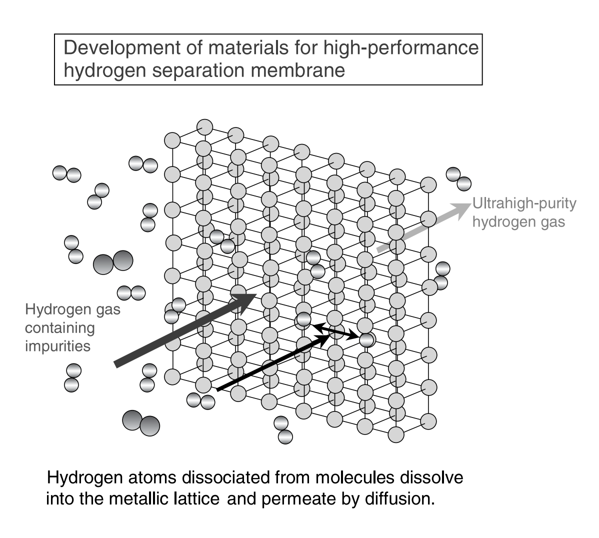


Figure 5 shows a metallic separation membrane used for purifying hydrogen by permeation. This membrane dissociates hydrogen to the atomic state on its surface, and only the dissociated hydrogen atoms can permeate through the membrane. As a result of the elimination of impurities and catalyst poisons, it becomes possible to operate hydrogen energy systems effectively. At present, the main material used for the metallic separation membranes is palladium of the platinum group, but it is now being attempted to obtain satisfactory results utilizing the vanadium recovered from petroleum combustion ash.

Other ecomaterials of the system component type include superconducting materials that are expected to significantly contribute to the efficient transport of energy, thermoelectric materials that enable recovery of energy from low-quality waste heat, and, in addition, heat resistant, abrasion resistant, and corrosion resistant materials required for power generation from waste.

4.2.5 Materials that support our daily life — Low-burden recycling type —

While the above-mentioned two types of ecomaterials actively serve environmental systems based on the characteristics and functions of the materials involved, materials of the low-burden recycling type are those used for everything that supports our daily life including buildings and household electric appliances. These are the materials that conform to material selection based on environmental consciousness.

The expression, "low environmental burden," means that products or materials bring about a low environmental burden in their total life cycle beginning with the resources recovery through the disposal after use and ending with waste treatment. And the method of assessing the environmental burden is called LCA (Environmental Life Cycle Assessment).

4.3 How are materials evaluated by LCA?

The environmental burden for a life cycle, BL, consists of the environmental burden of manufacturing, BP, the environmental burden of use, BU, the environmental burden of disposal of waste at the end of life, BE, and the deduction of burden due to recycling, BR.[5] Therefore, BL is given by the following equation:

$$\mathbf{BL = BP + BU + BE - BR} \quad \cdots\cdots (2)$$

If the performance of the material at the stage of use is P, by combining equation (2) with the aforementioned equation (1), the following equation (3) that expresses the environmental efficiency (EE) is obtained as follows:

$$\mathbf{EE = P/(BP + BU + BE - BR)} \quad \cdots\cdots (3)$$

Equation (3) enables the characterization of materials according to the term to which a particular material contributes.

Whereas ecomaterials were classified into three groups according to the way of action toward the environment in the preceding chapter, here in this chapter they are characterized by the type of environmental burden.

(1) Materials free of harmful substances (= materials with low BE)
(2) Materials with high material efficiency (= materials with high P or low BU)
(3) Materials with a history of low environmental burden (= materials with low BP)
(4) Recyclable materials (materials with high BR)

In the following section, the present status of materials development and the main points for each type are described.

4.3.1 Materials free of harmful substances

There are a group of materials widely spread in our daily life due to their special functions such as bondability, performance as film, and electric properties. These materials often contain components that turn out to be harmful when disposed. This occurs as a result of the attempt to keep the production cost at a low level. Now it is demanded to develop safe materials that provide the desired functions such as lead-free solder and dry cells containing no mercury. It is also hoped to develop materials that do not cause pollution by generating dioxin or environmental hormone. When attempting to replace harmful materials or structures intended for particular functions, it is necessary not only to avoid materials containing directly harmful materials but also to avoid materials that may generate harmful components at the stage of disposal. In addition to solder, although lead is widely used in plating, additives for lubrication, additives in metals for improving machinability, etc., now lead-free materials that provide such functions are being developed.

The use of cadmium and mercury is now almost limited to within controllable areas, and, although highly functional chromium plating is still being used, chromium-free plating technology is being developed.

Light emitting devices using gallium arsenide, widely used for cellular phones and CD-ROM drives, are another typical example of harmful material widely spread in the environment. When a harmful material cannot be replaced with other materials, it is necessary to thoroughly control the products. In the case of gallium arsenide, however, this is difficult to carry out, and, as such, the direction that should be taken in the development of materials is to aim at achieving high performance without using harmful substances.

4.3.2 Materials with high material efficiency

Examples of materials with high material efficiency are those related to the transmission, conversion and transportation of energy, that is, those used for the transmissions and light bodies of automobiles. In the case of these materials, the environmental burden caused by the energy flow during use is much larger than that in the production stage. Although it is important for these materials to have low environmental burden, it is still more important to achieve the intended role. Therefore, materials that provide effective accomplishment of intended services must be developed. Especially for raw materials, the environmental burden during use is often neglected, but results of LCA indicate that the environmental burden of materials used for automobiles during use is ten times or more compared to that of material production. Therefore, it is essential to select such materials that promote effective transmission or generation of energy by providing high-temperature, high-efficiency action based on weight saving and enhanced heat resistance, or by reducing energy loss in transmission operation caused by abrasion.

Many attempts have already been made to develop such materials from the viewpoint of energy saving, and the attempts must be positively enhanced from the viewpoint of reducing the environmental burden.

4.3.3 Materials with a history of low environmental burden

Materials with a history of low environmental burden are defined as those materials having a low environmental burden from the mining of resources to the production stage. Materials based on wood are ecomaterials in the sense that wood is regeneratable, whereas resources such as ores and fossil fuels are exhaustible. Plant-origin plastics synthesized from biomass without using petroleum also belong to this group. Materials made from the byproducts generated in the activities of human beings are another example of materials with a history of low environmental burden, and such materials contribute to reducing the burden for waste treatment. Eco-cement produced from industrial wastes, which are artificial resources such as incineration ash and polluted sludge, is a typical example. Another successful example is steel TULC cans. Steel sheets for TULC cans are polymer-coated so that lubricants are eliminated in the production process, thus reducing the generation of waste fluid to zero and drastically lowering the environmental burden of such production process. It is more than just process saving and energy saving to lower the environmental burden in the production process. New process technologies that reduce the environmental burden by utilizing low-grade resources and regenerated resources are now required.

4.3.4 Recyclable materials

Attempts for materials recycling are being made intensively with the establishment of the Basic Law for a Recycling-oriented Economic Society in 2000 as a turning point.

Recycling tends to be considered as an issue relating to the social system, process technology for recycling, and product designing. But materials themselves must not be neglected as the fourth aspect of the issue. As materials are usually composites with delicate differences in composition and complex treatments such as surface finishing, which cause degradation in the recycling process.

In his book,[6] Professor Kunihiko Takeda of Shibaura Institute of Technology describes the problems caused by contamination and degradation during recycling and the methods for assessment of recycling costs, and points out that at present the environmental burden increases as the number of recycling increases. Although this is a fair-enough point, we must construct a recycling-oriented society in the future because we live in a closed society on the earth in terms of materials, and, therefore, we must start to move forward to achieve this goal.

At present, as shown in Table 1, the ratios of recycling of most metals, which are exhaustible resources, are low, and we must take positive actions to improve the recyclability from the viewpoint of material technology. The following are approaches that should be taken.

(a) Material designing that does not include substances that disturb recycling processes.
(b) Material systems insensitive to inevitable artificial contaminants.
(c) Imparting functions that provide identification and decomposition to help recycling processes.

In order to achieve target (a), a design technology called "recyclable material design" is being developed, in which the high performance of a material is obtained by controlling the structure of materials of simple compositions without adding elements. A successful example of such materials is thin steel for automobile application. These steel sheets feature lightweight and strength as well as recyclability, because the amount of addition elements was reduced by increasing the strength of materials through heat treatment. Such a concept is now a major premise in the steel industry. In addition, in the super steel project [7] that aims at "double strength and double life," recyclabiliby is one of the major aspects of development.

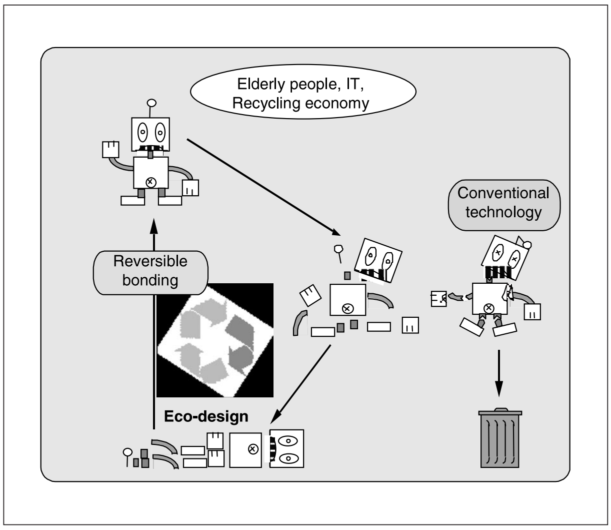
Examples of contamination relating to (b) are

Table 1: Recycling ratios of major non-ferrous metals in Japan

	Amount of consumption (tons)	Amount of discharge (tons)	Recycling ratio (%)
Copper	3,500 thousand	598 thousand	66
Aluminum	2,300 thousand	1,662 thousand	54
Zinc	1,000 thousand	364 thousand	20
Lead	300 thousand	277 thousand	66
Cadmium	2,000	1,080	28

Source: "Recycling-oriented economic system to be achieved for non-ferrous metals" 1999, the Ministry of International Trade and Industry.

Figure 6: Conceptual diagram for easily detachable bonding technology



Source: Web site of the Nanometer-scale Manufacturing Science Laboratory, Research Center for Advances Science and Technology, The University of Tokyo.[9]

copper and other materials in iron scraps derived from electric cables and metals such as tin coming from surface plating. There is also an attempt to positively utilize impurities and new research is being made to improve strength and ductility of steel by controlling fine structures through the use of impurity copper.[8]

Target (c) is a new approach of improving bonding technology that enables the recovery of usable components and the reuse of discarded parts. As an example, Figure 6 shows a conceptual diagram of easily detachable bonding technology. For detaching, a method utilizing the cubical expansion caused by hydrogen absorption has been proposed.[9]

Relating to recycling, one thing we must pay attention to is that recycling heretofore has mostly involved in-house scraps and process scraps whose origins are clear. Recycling of used materials that include scraps of various shapes, impurity ingredients, and composites is a challenging technical subject, and research is just going to be started.

4.4 National policy and organization

In "The Basic Plan for Science and Technology" endorsed by the Cabinet in 2001, four priority fields of science and technology — "life science," "information and communication," "environment," and "nanotechnolgy and materials" — are listed, so that investment and research and development are conducted strategically. Furthermore, in the "Policy for Allocation of Resources Including Budget and Human Resources Relating to Science and Technology in Fiscal 2003" prepared by the Council for Science and Technology Policy this June, "materials required for the enhancement of environmental protection and efficient use of energy" are clearly designated as related to the above-mentioned "nanotechnology and materials." "Ecomaterial" is an important concept that covers both the environment and materials, and combines them.

Japanese institutes and associations have established various study groups and special interest groups as shown in Table 2. The Society of Chemical Engineers, Japan, The Chemical Society of Japan, and other institutes and associations related to chemistry are also carrying out strenuous activities from the viewpoint of process with the "environment" as the keyword. And almost all of their bulletins feature special articles every month relating to the environment and material processing.

Many international conferences are also being held. Since "ecomaterial" is a concept created in Japan, as described at the beginning, Japan is playing a center role in the international conferences. Table 3 shows major examples of international conferences. In these conferences, stress is being laid on "what we should do to construct an integrated social system for environmental protection, whereas all the separate measures for environmental protection such as various tools including LCA, zero emission, promotion of recycling, and restriction of harmful substances have been implemented." [4]

The Ecomaterials Center was established in April of this year in the Independent Administrative Institution, National Institute for Materials Science as a parent organization for the promotion of research on ecomaterials. The center consists of four groups — Eco-Circulation Processing, Eco-Device, Eco-Energy Materials, and Eco-Function Materials — with a total of 65 members including 23 permanent researchers. Research organizations named with the term "ecomaterial" do exist hitherto at the level of laboratory or research

Table 2: Study groups and special interest groups of Japanese institutes and associations related to ecomaterials

Society of Non-traditional Technology	Ecomaterials Forum (established in 1993)
The Society of Polymer Science, Japan	Ecomaterial Study Group (established in 1992)
The Japan Institute of Metals	Ecomaterial Study Group (established in 2000)

Table 3: Major international conferences related to ecomaterials

International Conference on Ecomaterials	Held every other year since 1993, the fifth conference held last year
International Conference on EcoBalance	Held every other year since 1994, the fifth conference held this year
International Conference on Ecodesign	Held every other year since 1999, the second conference held last year

department — the Ecomaterial Group of the National Institute of Advanced Industrial Science and Technology for example. However, the Ecomaterials Center covers all the fields relating to ecomaterials as shown in Figure 2 — Eco-Circulation Processing corresponds to the low-burden recycling type, Eco-Energy Materials correspond to the system component type, and Eco-Function Materials correspond to the function-providing type — and further include the Eco-Device Group that aims to establish the technology for preparing devices harmonious with the environment. Thus, the target of the Ecomaterials Center is to become an integrated parent organization for the development of ecomaterials.[10]

4.5 Accomplishments of ecomaterials research

Since the concept of "ecomaterial" was presented to the world from Japan for the first time in 1991, research projects relating to ecomaterials have been continuously carried out mainly supported by promotion expenditure. Due to the results of these projects and increasing concern about global environmental issues, the term "ecomaterial" is now being used even in the advertisements of private companies' products as well as within manufacturing premises. Also, some departments of universities use this term for their names and the term is steadily penetrating into society. The activities in the past have a great significance in that researchers and engineers now consider, when designing practical materials, conformity with the environment in addition to the improvement in performances and functions that have been the main concerns.

One of the most important achievements of research on ecomaterials is the proposal of MLCA (Materials LCA). In the past, only LCA for products (PLCA = Products LCA) was made. In the PLCA, consideration for the environment relating to materials was at most something like "the environmental burden of a part should be reduced because the present value is high." Environmental burden of materials, that is the index of ecomaterials, is now being established with the progress of MLCA. MLCA not only provides a valuable database for PLCA but also enables grasping the flow and circulation of materials macroscopically as well as microscopically.

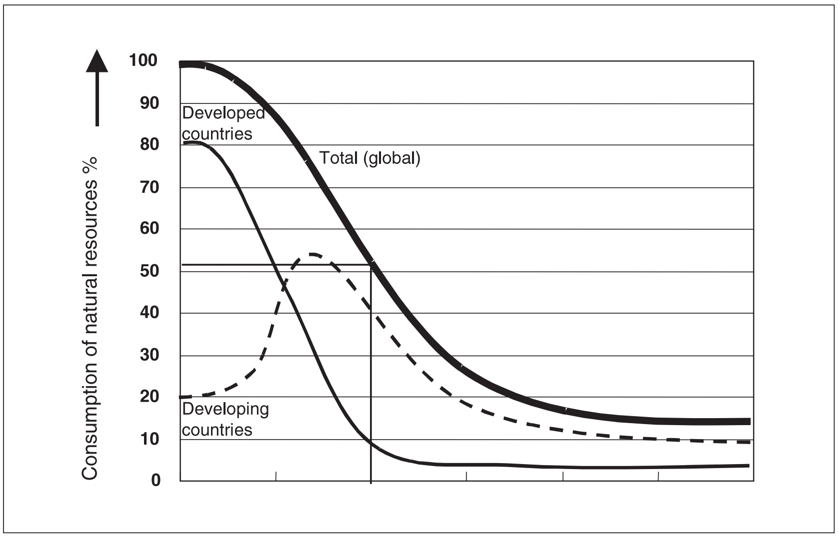
Another important achievement is the proposal of recyclable materials design. The concept of resources circulation in which properties of materials with simple composition should be improved by controlling fine structures and not by addition elements was created in the discussion of ecomaterials at the initial stage. This concept is the core idea of the "Super Steel Project" and also the guiding principle for many research projects for materials.

Since research on ecomaterials is still in the early stage, no ecomaterials in practical use have been developed. However, some structural materials including super steel have reached a stage that requires just one more effort. Furthermore, wood ceramics based on natural raw materials have been developed triggered by the project.

4.6 Keywords for the future: improvement of resource productivity

Taking into consideration that the basis of the environmental problem is the enormous consumption of materials and disposition of materials, the fundamental idea for developing ecomaterials lies in the "improvement of resource productivity." "Resource productivity" is an expression used in terms of global environmental issues, and analogous to economic terms such as capital productivity and labor productivity. Resource productivity is defined as the efficiency of performance of products and systems relative to the total input of various resources and energy. Weizacker of Germany described the importance of resource productivity in an easy-to-understand manner as "to double the affluence while reducing the material consumption to half," and propounded "Factor 4" that aims to reduce the consumption of materials per unit service to a quarter. Furthermore, Schmidt-Bleek of Wuppertal Laboratory propounded "Factor 10," claiming that developed countries must reduce materials consumption to one-tenth of the present amount.[11] They argue as follows (see Figure 7). At

Figure 7: Reason for Factor 10

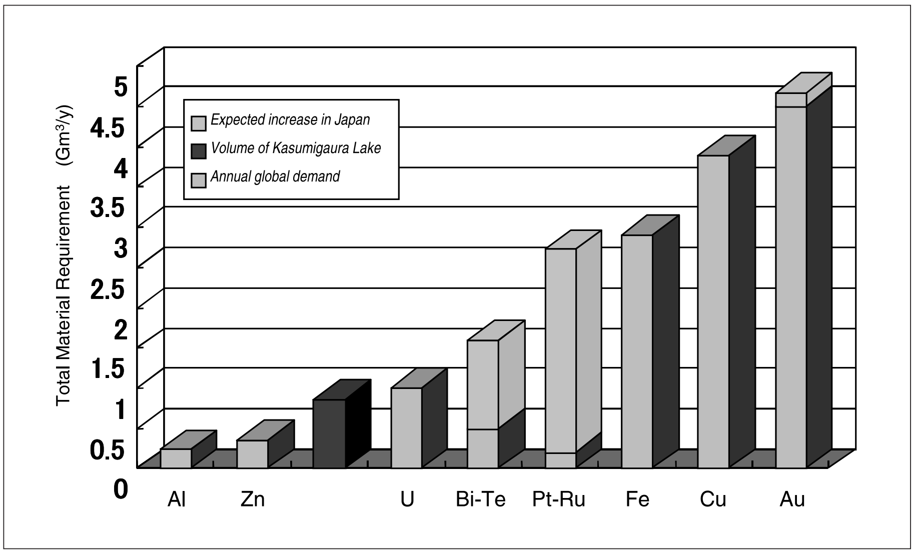


present, developed countries whose population is 20% of the world's total of six billion consume 80% of the total resources. Assuming that the resource consumption by developing countries increases by a factor of a little less than three from now forward, in order for human beings to maintain production activities for 100 or 200 years, it is necessary to reduce the consumption of natural resources to 50% of the present consumption in 50 years, keeping pace with the curve expressed by the heavy line in the figure. To realize this, developed countries must reduce their present consumption of resources to one-tenth (curve expressed by the thin line).

TMR (Total Material Requirement) is a parameter that indicates how much total resource is taken from the global environment. Figure 8 shows a graph of TMR for the annual consumption of metals in the world. The third column from the left side shows the total amount of water in Kasumigaura Lake for reference. It is seen that soil amounting to five times the volume corresponding to that of Kasumigaura Lake is dug out, generating the same amount of waste soil as an environmental burden. Likewise iron generates waste three times the volume of Kasumigaura Lake. In order to reduce this TMR, it is necessary to develop recyclable materials that reduce the burden on the earth as well as to develop materials that provide high performance using less amount of resources with low TMR — that is materials of high resource productivity.

In addition, future requirements for materials in Japan are added in Figure 8 (light-colored portions of the columns). In the case of catalyst materials used for fuel cells, which are now drawing public

Figure 8: Total material requirement for annual demands of metals in the world



attention, although the amount actually used is very small, large amounts of resources are used for their production. If all the automobiles in the future use fuel cells and the technologies to produce materials are not changed, the filled portions of TMR for Pt-Ru and Au will be increased so that the total is almost comparable to the TMR caused by iron in the world. In the case of the thermoelectric materials (Bi-Te), which is expected to be used for waste heat recovery, resource consumption equal to 1.5 times the volume of Kasumigaura Lake will be induced when 5% of the total power generation in Japan is produced using this system. This is the situation in Japan where the utilization of materials is saturated, and efforts are being made to reduce the consumption of resources by transiting to a recycling society. From now on, people of many Asian and African countries will aspire toward more affluent life bringing about enormous needs for automobiles, semiconductors, energy and so forth. Then, it will be impossible to cover all of these requirements with the present resource productivity for both structural and functional materials. It is therefore necessary to innovatively increase resource productivity, so that the expected drastic increase in materials and energy demands in developing countries can be satisfied.

4.7 Conclusion

In the United Nations Conference on Environment and Development held in Rio de Janeiro in 1992, which corresponds to the 20th anniversary of the United Nations Conference on the Human Environment held in Stockholm, an action plan for relieving the global environment, "Agenda 21," was formulated. However, the report, "Implementation of Agenda 21," published at the end of last year points out that we are far behind the agreed target set in Rio and the situations in some fields are worse than 10 years ago.

In response to the above-mentioned report, the action plan adopted by the Environmental Development Summit clearly states, in addition to a recommendation for the eradication of poverty, the following targets: "utilization of technologies for clean and efficient energy," "prevention of the generation of industrial wastes, promotion of recycling and use of substitute materials that are environmentally friendly," restriction of harmful chemical substances and review of manufacturing methods" and "prevention of the depletion of natural resources." These items exactly represent the viewpoints of ecomaterials, which aim to conform to the environment and achieve a sustainable society.

Considering the fact that it takes a long time to establish material technologies and put them to use, actions must be enhanced at the national level. Fortunately, Japan is now leading the world in the field of ecomaterials. Deployment of ecomaterials to developing countries is an urgent task for the sake of solving global environmental problems, but it will also bring about a large economic effect to Japan.

Since the research on ecomaterials covers wide and interdisciplinary areas, it is necessary to build a network of many researchers and engineers. Therefore, research works must be carried out with the collaboration of all Japanese researchers related to this subject with hub organizations as the cores.

It is possible to obtain the environmental efficiency of individual ecomaterials based on MLCA, which indicates the grade of ecomaterials. However, it is another question whether the sum total of the efficiency values indicates the environmental efficiency of the total system, enabling optimization of the over all environmental efficiency. In order to correctly assess the over all environmental efficiency, although it is important to carry out research works with close collaboration among technical fields, it is still more important to continuously consider the relationship between materials and society.

While it is an important issue for researchers engaged in materials development and people related to policy making for science and technology to coordinate the relationship between materials development and society, it seems very difficult to find a solution. However, the relationship between the environment and society appears to be very close and realistic to us. In Chapter 4-4, it was described that "ecomaterial" is an important concept that combines the environment and materials, but it may be further amplified as a concept that combines society and materials. The perspective of ecomaterials is the key to clarifying the interface between society and materials through the viewpoint of the environment.

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References

[1] Rare Metals Forum Investigation and Research Report "Ecomaterials (I)," Rare Metals Forum, Society of Non-Traditional Technology (1991).

[2] All about Ecomaterials, Nippon Jitsugyo Publishing Co., p. 23 (1994).

[3] Green Chemistry — Chemistry for a Sustainable Society, Kodansha, p. 52 (2001).

[4] Harada, Energy and Resources, vol. 23, No. 1 (2002).

[5] K. Harada, Presented in The First Materials Forum on Future Sustainable Technologies, September 17-20, 2002, Augsburg, Germany.

[6] Kunihiko Takeda, "Recycling" Polluted Archipelago, Seishun Publishing Co. (2000).

[7] For example : "Trends in Research and Development of Fine-grained Metallic Materials," Science & Technology Trends – Quarterly Review No.6 (Feb. 2003).

[8] H. Kakisawa et al., Materials Transactions, Vol. 42, No. 3, p. 301 (2002).

[9] Nanometer-scale Manufacturing Science Laboratory, Research Center for Advanced Science and Technology, The University of Tokyo, http://www.su.rcast.u-tokyo.ac.jp/index-j. html.

[10] Ecomaterial Center, Independent Administrative Institution, The National Institute for Materials Science, http://www.nims.go.jp/ecomatecenter/.

[11] Friedrich Schmidt-Bleek, Wieviel Umwelt braucht der Mensch? MIPS-Das Mas fur okologisches Wirtschaften, Birkhauser Vealag, Berlin/Basel/Boston 1994

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